HELIOCOMM: Wireless Controls State-of-the-Art Report

Eirini Eleni Tsiropoulou, Aisha B. Rahman, and Md Sadman Siraj

University of New Mexico

NREL Technical Monitor: Matthew Muller

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Deliverable 1.1: Wireless Controls State-of-the-Art Report

SECTION I: COVER PAGE

a. SETO ID Number	*38488-002*	
b. NREL Award Number	*SUB-2023-10300*	
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h. Report Term or Frequency	*Quarterly*	End: 04/06/2023
i. Subaward Principal Investigator (PI)	*Name: Eirini Eleni Tsiropoulou* *Title: Assistant Professor* *Email address: eirini@unm.edu* *Phone number: +1-469-216-6120*	
j. NREL Technical Monitor	*Name: Matthew Muller* *Title: Technical Monitor* *Email address: matthew.muller@nrel.gov* *Phone number: -*	
k. Certifying Official (if different from the PI or BC)	*Name:* *Title:* *Email address:* *Phone number:*	

Signature of Certifying Official ____________________ Date ____________

[1] If you have received No Cost Time Extensions (NCTE), please add a note below the table indicating the length of each one and which budget periods were affected.

SECTION II: EXECUTIVE SUMMARY

This report introduces the concept of wireless controls in heliostat-based concentrating solar thermal power (CSP) systems. Specifically, the need for wireless communications to be implemented within the heliostat-based CSP systems is identified versus the existing approaches that follow wireline connections which suffer from high installation, operation, and maintenance cost. Furthermore, this report analyzes the most recent advances in the field of developing wireless controls in heliostat-based CSP systems, which are highlighted to be in their infancy given the primitive wireless networking solutions that they currently utilize and test. The main contribution of this report is the introduction of a novel HELIOCOMM system that supports the wireless controls in heliostat-based CSP systems by exploiting the next generation networking technology of integrated access and backhaul. Furthermore, the proposed HELIOCOMM system performs an artificial intelligent clustering approach of the heliostats and clusterhead selection and develops an entropy-based routing model to enable the heliostats to communicate with the central station by considering their energy availability and network traffic. Also, towards efficiently exploiting the limited resources in the developed wireless communication system, a resource allocation module is introduced that performs the maximization of the energy efficiency of each heliostat by minimizing its corresponding experienced end-to-end latency to communicate with the central station, while performing an intelligent bandwidth splitting in the access and backhaul wireless links. The overall architecture is presented, and its individual building components are discussed in detail.

SECTION III: Wireless Controls State-of-the-art Report

A. Wireless Heliostats: A Need rather than a Desire

Heliostat-based concentrating solar-thermal power (CSP) systems have been deployed around the world providing a green source of energy that has the potential of eliminating the carbon footprint of energy production and combating climate change. Examples of existing CSP systems include the Ashalim power station in the Negev desert, Israel *[1]*, the Mohammed bin Rashid Al Maktoum Solar Park in Saih Al-Dahal, United Arab Emirates *[2]*, the Redstone Solar Thermal Power in Postmasburg, in the Northern Cape Region of South Africa *[3]*, the Ivanpah Solar Electric Generating System in California, USA *[4]* and many more around the world. The common challenge of the CSP systems is the high installation, operation, and management cost, which stems from a wide variety of sources ranging from the heliostats' mechanical parts cost to the mirror cleaning to the closed-loop controls and autocalibration of the heliostats in an online manner, just to name few.

Focusing on the closed-loop controls, they can be used to support several types of functionalities, like automatic calibration of the heliostats, collect data about the soiling level of the heliostats, canting error correction, and others. Currently, the closed-loop controls are supported by wired connections established in the heliostat-based CSP systems, which suffer from high installation and maintenance cost, as they currently use buried copper or fiber optic wired networks. The wired communications solutions are characterized by high cabling-related cost (installation, maintenance, operation-related costs), which makes them less applicable in future heliostat-based CSP systems, especially deployed in a large-scale setup (larger heliostats fields with larger number of connected heliostats). Therefore, developing a wireless heliostat-based CSP system that can support the wireless controls of the heliostats is a real need rather than a desire for the next generation heliostat-based CSP systems *[5]*.

The existing heliostat-based CSP systems are developed following a set of homocentric circular or semicircular arrays of heliostats communicating with a central station that is mounted at the ground level of the tower, where the control room of the heliostats-field resides. The existing wired communication solutions enable the heliostat-to-central-receiver direct communication through the buried copper or the fiber optic links and they mainly cover fields at the order of magnitude of few kilometers radius from the central receiver and tens of thousands of connected heliostats *[6]*. An example heliostat-based CSP system's topology and wired communication based on buried copper or the fiber optic links is presented in *Figure 1*.

Next generation heliostat-based CSP systems are envisioned to cover an area with radius ranging from 1 km to 5 km, supporting a number of connected heliostats that will range from hundred to several hundreds of thousands, e.g., 70,000 connected heliostats. Apparently, the installation, maintenance, and operation-related costs of the wired communications solutions will be huge in large heliostat-based CSP systems, thus, the wireless controls of the heliostats are a pressing need. The latter one is aligned with the goal of the U.S. Department of Energy to lower the heliostats cost from \$150/m^2 to \$50/m^2.

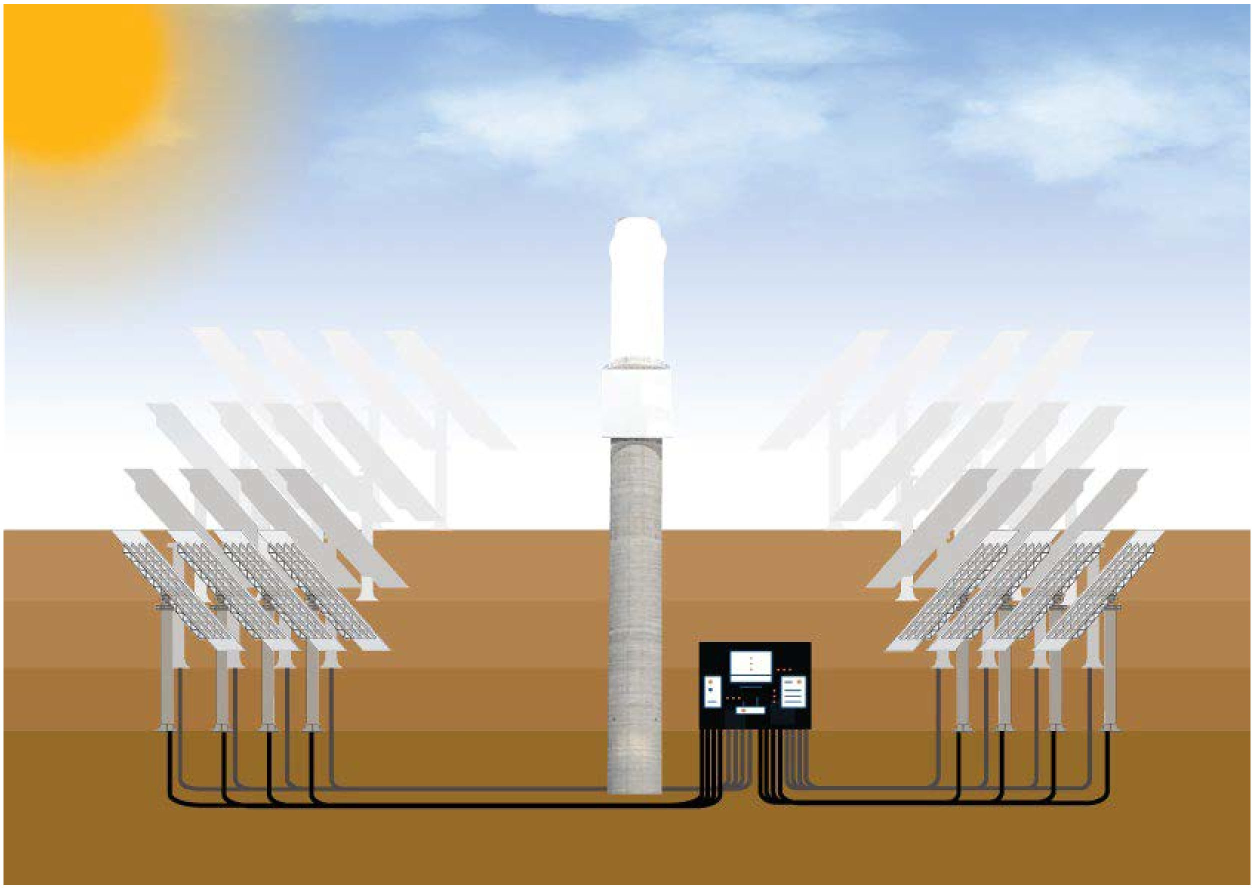

Figure 1 Example heliostat-based CSP system's topology and wired communication based on buried copper or the fiber optic links.

Focusing on the wireless controls of the heliostats, the wireless communication of the heliostats' transceivers and the central station that is located at the tower of the CSP system, consumes energy. Currently, the vast majority of the existing heliostat-based CSP systems provide energy to the heliostats in a wired manner. Therefore, in order to realize a fully wireless controls system in the heliostat-based CSP systems, both the communications as well as the powering of the heliostats should be performed in a wireless manner. In order to achieve the latter goal, photovoltaic (PV) panels and batteries are attached to each heliostat in order to harvest energy and support several functionalities of the heliostats, such as the control of its mechanical parts for beam pointing and automatic calibration, collect data from actuators that are attached to the heliostats, such as cleaning, the canting error, the elevation, and the azimuth, and support the wireless communication with the central station. However, the performance of the energy harvesting of the PV panels can substantially vary due to weather conditions, e.g., cloudy, rainy days, night period, and soiling level on the heliostats. Thus, ensuring that sufficient energy is available to support the wireless communication between the heliostats and the central station is of paramount importance to guarantee the stable and undisrupted online control of the heliostats.

In the following section, we analyze several wireless communications approaches that have been attempted to support the heliostat-based CSP systems.

B. Wireless Heliostats Field: A Multi-Cellular Architecture

The implementation of wireless communications and controls in heliostat-based CSP systems is quite at its infancy. Adopting a fully wireless control system, coupled with a wireless power source can cut the cost of power and control by 42%, according to the comprehensive study and investigation by *[7]*. To replace the fully wired system in the heliostat field with a wireless model, the concept of shared nodes was adopted in *[7]*,where the shared nodes wirelessly communicate with each other or with the central station. Given the specific examined topology, the candidate technologies for the wireless communication of the shared nodes were ZigBee, Wi-Fi (2.4 GHz, 5 GHz and 60 GHz), cellular, and satellite. Among the technologies, Wi-Fi 5 GHz was chosen to ensure the reliability of the wireless control signal propagation in the heliostat field. Wi-Fi 5 GHz adapts to the standards of IEEE 802.11, thus, offering both long range and high data rate. Another study on candidate wireless technologies for modular heliostat fields, specifically adapting the HelioPod technology developed by the Solar Thermal Energy Research Group (STERG) at the University of Stellenbosch, South Africa is provided in *[8]*. The comparative study included the following wireless technologies – LoRa, NB-IoT, BLE, ZigBee, and Wi-Fi 5, Wi-Fi 6, and Wi-Fi HaLow. Considering the scalability and flexibility requirements in terms of topology, Wi-Fi 6 was selected as the best-suited wireless technology for the selected modular heliostat field. Wi-Fi 6, also known as the IEEE 802.11ax standard incorporates both 2.4 GHz, and 5 GHz ISM bands, allowing scan and select channels to adjust between frequencies to accommodate short-distance and long-distance communication. Moreover, Wi-Fi 6 can support, simultaneously, 8 streams owing to the incorporation of Multi-User Multi-Input Multi-Output (MU-MIMO) and Orthogonal Frequency Division Multiple Access (OFDMA) techniques.

The competitiveness of wireless communications for heliostat-based CSP systems was also studied, specifically in terms of scalability, in the HelioMesh project *[9]* where dedicated protocols for the wireless controls of the heliostats were defined. The transceivers employed in the heliostat node, called the HelioNodes, are IEEE 802.15.4-2006 compliant with 16 non-overlapping channels. Furthermore, to avoid collision within a channel, Carrier Sense Multiple Access (CSMA) technique is adopted. Moreover, multiple routing protocols are supported in the mesh network in order to boost the reliability of the system. A field test was conducted at the DLR Solar Demonstration Tower Plant in Julich, Germany for a performance evaluation of the practicality of the HelioMesh project. Furthermore, the reliability of wireless controlling through IEEE 802.15.4 standard in a large heliostat mesh network in emergency situations such as the need of emergency shutdown, was tested through a simulation in *[10]*. A novel Connected Graph Set (CDS) based broadcasting algorithm was developed focusing on broadcasting without causing high information and control overhead in the network. Since none of the available CDS algorithms were applicable to large heliostat fields communicating via IEEE 802.15.4 modules *[11]* a novel CDS algorithm combining an acknowledgement algorithm had to be developed. Further research on the applications of IEEE 802.15.4 for heliostats field control, adopting the concept of wireless sensor networks (WSN) can be found in *[12]* and *[13]*.

The most recent advances in the field of developing wireless controls heliostat-based CSP systems have been focused on adopting a multi-cellular architecture with frequency reusability. This development has been introduced by Brightsource Industries (Israel) LTD. *[14]* and can be applied in several heliostat-based CSP systems, where Brightsource Industries (Israel) LTD has developed its own proprietary projects, such as:

1. Ashalim Plot-B central tower CSP in Israel: 50,600 heliostats, size of each heliostat 20.7/m^2, 1.3-km radius,
2. The Noor Energy 1 in Dubai: 70,000 heliostats, size of each heliostat 26/m^2, 1.7-km radius, and
3. Redstone in South Africa: 40,000 heliostats, size of each heliostat 26/m^2, 1.5-km radius.

The common characteristic of those deployments is that the heliostat-based CSP system is divided into multiple cells, where at each cell an access point is deployed, communicating in a wired manner with the heliostat array control system, as presented in *[14]*. On the other hand, each access point supports the wireless communication with a statically or dynamically selected set of heliostats, where the latter ones are associated to the access point through a proprietary deployed programmable heliostat control system. The assignment of heliostats to the access points can be static, i.e., pre-determined, or dynamic by changing from time to time and then, remaining static for days, months, or years. The multiple access points communicate in a wired manner with a master control system that resides in the central heliostat field control room. An indicative multi-cellular wireless controls topology in a single-tower heliostat-based CSP system is presented in *Figure 2*.

Several frequency bands are envisioned to be used, while all of them are industrial, scientific, and medical (ISM) bands in order not to interfere with their usage for other applications, e.g., telecommunications. The non-license ISM bands that are envisioned to be used are 902-928 MHz, 2400-2483 MHz, and/or 5150-5825 MHz. The adoption of an ISM band depends on multiple factors, such as the communication distance among each heliostat and its corresponding affiliated access point depending on the heliostats field size, the external and internal interferers, the weather conditions affecting the communication channel gain conditions, the shadowing and multipath phenomena, the electromagnetic interference stemming from the heliostats themselves, the latency and energy consumption constraints, and others. Some of the currently adopted bands for wireless controls are 915 MHz band for US and 868 MHz band for Europe. Thus, the selection of the most appropriate ISM band is part of the wireless controls optimization process, and highly depends on the specific characteristics of each heliostat-based CSP system, e.g., field size, energy availability from the PVs, battery capacity, and others.

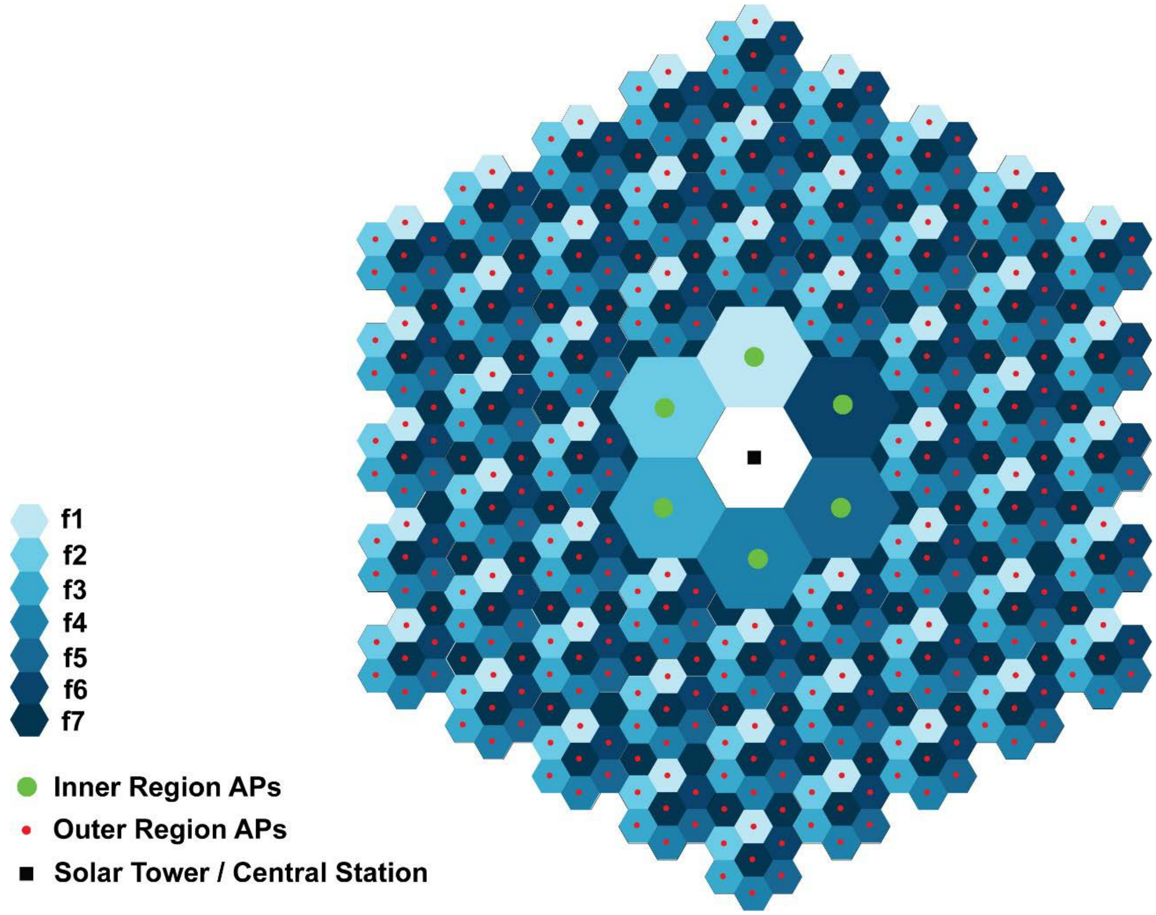

Figure 2 Multi-cellular wireless controls topology in a single-tower heliostat-based CSP system.

After the selection of the ISM band to be used for wireless communication in the field, the corresponding bandwidth is split into sub-channels of typically 1 MHz to be reused among neighboring cells. Different patterns of bandwidth splitting into sub-channels are also considered, e.g., 0.5 MHz, 0.9 MHz, 1.5 MHz, or 2 MHz subchannels, mainly depending on the cells' density, the frequency reuse factor, the targeted data rate, the latency and energy consumption requirements, and others. The deployment of the access points in the CSP system follows the requirements of satisfying the coverage and connectivity requirements, especially by considering the interference and jamming sources. The access points can be deployed in two different ways: (i) either by installing access points in several pre-identified places in the heliostat field at a height of 10 m – 15 m above the ground to mitigate the radio frequency and electromagnetic interference, or on top of preselected heliostats at a height larger than 10 cm above the heliostats for the same reasons. The access points can be equipped with omni- directional antennas to cover a larger circular area or a directional antenna to support the spatial diversity and better exploit the limited bandwidth, while further mitigating the interference in the search segment. Each access point can act as a transceiver by transmitting to and receiving data from the heliostats that are associated with it. The heliostats association to the access points can be performed in a dynamic manner by considering several factors, such as communication channel gain conditions, interference levels, heliostats energy availability, network traffic, etc., and it is an open research challenge that has not been explored in the existing literature.

Focusing on the architectural deployment of the access points in the heliostat-based CSP system, Brightsource Industries (Israel) LTD is currently the main industrial company that has introduced the concept of creating zones/regions within the heliostat field. Specifically, the heliostats field with maximum radius from the solar tower 1.3 km – 2 km is divided into two regions, i.e., the inner and the outer region. The outer region is more susceptible to radio frequency and electromagnetic interference, as well as to jamming, thus, the deployment of the access points is denser. The typical coverage radius of an access point at the outer region is 10 m – 100 m, while the corresponding radius in the region inner region is 75 m – 100 m. The average distance between two access points in the inner region ranges between 100 m – 200 m, while the corresponding distance in the outer region is smaller, i.e., 10 m – 100 m. The maximum radius of the inner region with center the solar tower is approximately 100 m, while the distance of the border of the outer region from the inner region's border can be even up to 1 km. Apparently, the size of the cells in the outer region is smaller than the one in the inner region, and some, if not all, access points in the outer region communicate with the master control system via wired communication system. A representation of the inner and outer regions in a single-tower CSP and repeaters deployment is presented in *Figure 3*.

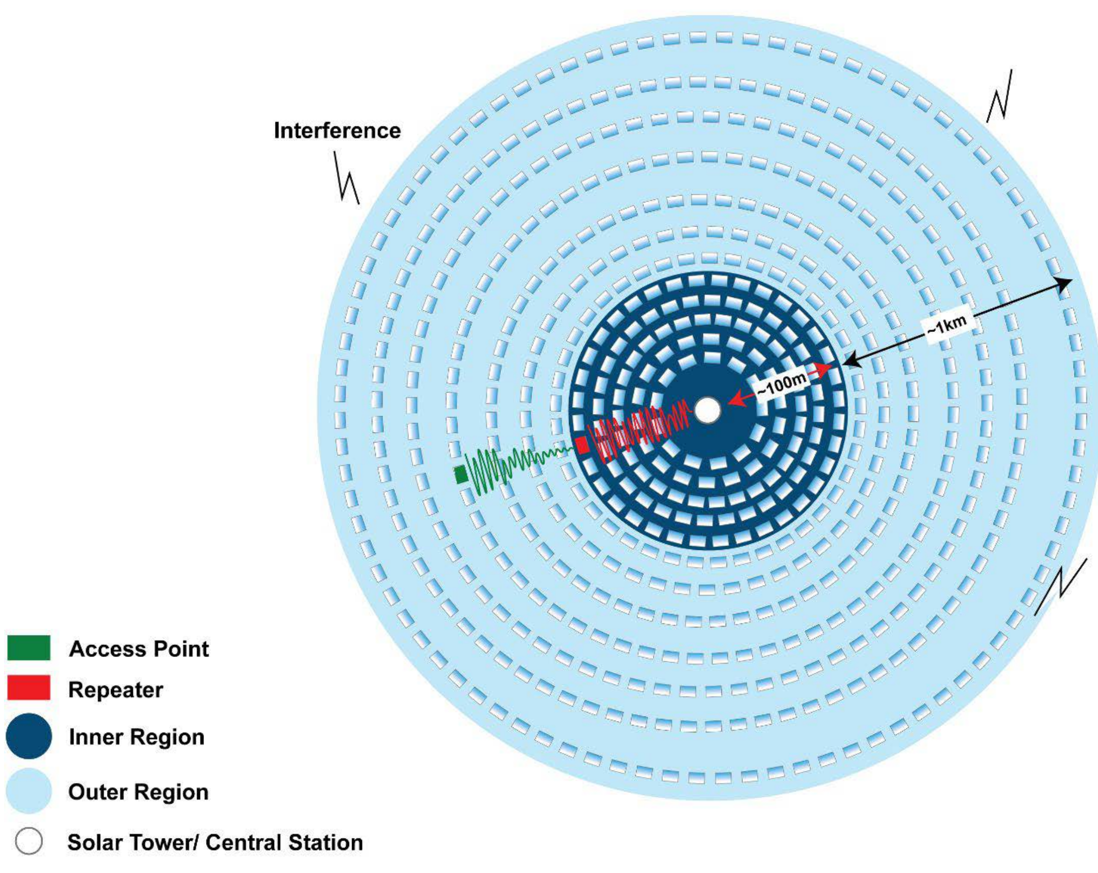

Figure 3 Inner and outer regions in a single-tower CSP and repeaters deployment.

Given the deployed access points in the CSP system, some heliostats transceivers belonging in the inner region may be "recruited" by their access points to act as repeaters of the signals transmitted from the outer region. The latter functionality is necessary due to the signals that attenuate in long distances, i.e., from an access point residing in the outer region to the master control system at the solar tower. In practical implementations of the above-described access points deployment pattern, the density of the access points developed in the outer region is at least 30% greater than the corresponding density in the inner region *[14]*. Also, given the higher possible interference levels at the outer regions, the wireless communication among the heliostats and their associated access point typically utilizes higher power levels compared to the corresponding communication in the inner region. Furthermore, different communications protocols can be used in the inner and outer regions. Specifically, the wireless communication protocol used in the outer region should be characterized by higher noise mitigation capabilities. Thus, a wireless communication protocol in the outer region that employs space-time block coding, supporting lower data rate is more appropriate to improve the signal to noise ratio in the outer region.

C. Ashalim Use Case Scenario

Ashalim Plot-B is a single-tower CSP system residing in the Negev Desert in Israel and consisting of 50,600 heliostats that are controlled in a computer-based manner. The Ashalim Plot-B CSP system has an installed capacity of 121 MW and can produce on average 320 GWhr of energy per year. This single-tower CSP system has one of the tallest solar towers in the world (260 m), ranking second after the Noor Energy 1 in Dubai, which has a 262.44 m tall solar tower. The size of each heliostat in the Ashalim Plot-B CSP system is 20.7sqm and the heliostats field has a radius of 1.3 km from the center-solar tower *[15]*. The Ashalim Plot-B CSP system has adopted the multi-cellular wireless controls topology, as discussed in the previous section, where pre- deployed access point towers have been installed in the field.

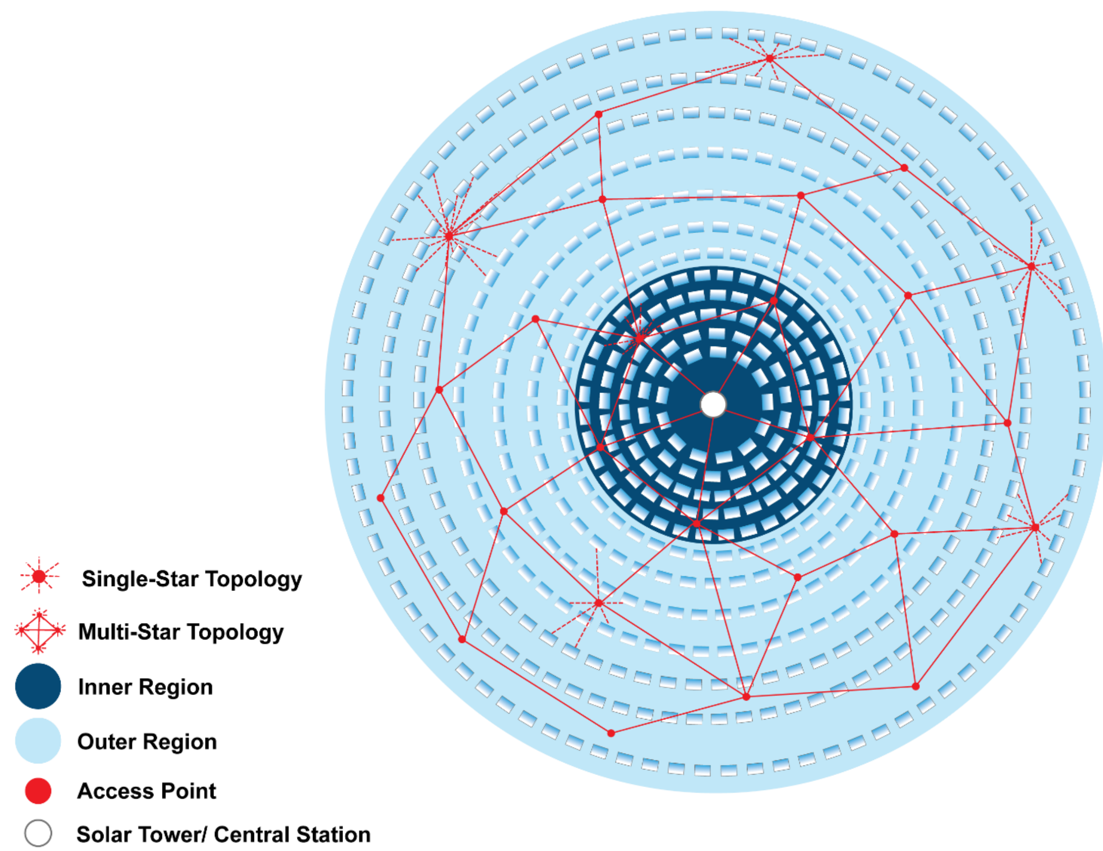

Figure 4 Multi-star wireless controls topology in a single-tower CSP system [14]**.**

Specifically, the wireless controls topology that is used follows a multi-star topology with multiple connections among the individual single-star topologies. Specifically, the central station of Ashalim Plot-B CSP system resides at the solar tower and a set of access points is deployed in the inner region, while a larger set of access points is developed in the outer region of the heliostats field. Each access points communicates with 500 or 1,000 or 1,500 or 2,000 or more heliostats connected to it following a single-star topology and the multiple access points communicate with the central station also following a single-star topology, thus, creating a multi-star hierarchical wireless communications topology *[14]*. The heliostats are dynamically deciding to which access point to get connected to and a heliostat can be connected to multiple APs. There is also the capability of multiple access points communicating among each other following also a mesh networking topology for overall field planning and maintenance purposes. The communication among each heliostat and its affiliated access point is bidirectional, where the heliostats transmit data from their controllers to the access point for further processing in the uplink communication, and also receives data regarding how it should adjust its open-loop controls from the access point in the downlink communication. The developed wireless control solution needs to support fast transmission of small amount of information in the vast majority of the cases of communication among the heliostats and the access points, as well as large amounts of information in the cases of software updates. The multi-star wireless controls topology in a single-tower CSP system is sketched in *Figure 4*. Each heliostat is equipped with a PV and a battery, as well as several actuators and sensors are attached to the heliostat. Part of the energy harvested by the PV is used to support the heliostats mechanical operation, power up the actuators and the sensors, and also support the wireless communications. Major motion commands are exchanged among the access points and the heliostats, thus, a large portion of the PV's harvested energy is utilized to support the operation of the heliostat's actuators.

D. Alternative Existing Wireless Communications Technologies

In this section, an overview is provided regarding alternative wireless communications technologies that are currently considered in the existing literature as candidate technologies to support the wireless controls in heliostat-based CSP systems.

1. **IEEE 802.11ax (Wi-Fi 6/6E):** Wi-Fi 6/6E operates at high frequency bands *2.4 GHz and 5 GHz/6 GHz* and it can support data rates ranging from *600.4 to 9607.8 Mbit/sec*. The typical range of Wi-Fi 6/6E is up to *120m* in outdoor environments. The *Orthogonal Frequency Division Multiple Access (OFDMA)* is adopted to support the simultaneous transmissions of the wireless heliostats modules, while mitigating the interference given the adopted OFDM technique. Different modulation techniques are used depending on the size of channels that are used, e.g., 20 MHz, 40 MHz, 80 MHz, 160 MHz channels, ranging from Binary Phase-shift keying (BPSK) to Quadrature Phase Shift Keying (QPSK) to 16/61/256/1024 Quadrature Modulation (QAM). The 20, 40, 80, and 160 MHz channels can be divided into 56, 512, 1,024, and 2,048 subcarriers. The subcarriers can be grouped into resource units supporting the dynamic spectrum management and different transmission power level can characterize each resource unit, allowing multiple heliostats wireless modules to transmit at the same time over the same spectrum band.
2. **IEEE 802.15.4 (Zigbee):** Zigbee operates at low frequency bands, typically, *868.0–868.6 MHz* in Europe, *902–928 MHz* in North America, and *2400–2483.5 MHz* worldwide use. The typical achieved data rate ranges at the levels of *250Kbps* with a typical range *10-100m* for line-of-sight communication. The *Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) or the Time Division Multiple Access (TDMA)* techniques are adopted *[8]*. The Zigbee protocol-based wireless modules operate in lower transmission power levels compared to the Wi-Fi 6/6E wireless modules.
3. **LoRa (Long Range):** LoRa operates at low frequency bands, i.e., *863–870/873 MHz* in Europe and *902–928 MHz* in North America. The achieved data rates range from *0.3 kbit/s to 27 kbit/s*, thus supporting long-range transmissions with low power consumption, as compared to the Zigbee protocol. The typical range of the LoRa protocol is *4.8 Km* in urban areas and *16 Km* in rural areas, assuming line of sight communication. LoRa uses a proprietary Spread Spectrum multiple access technique, called *Chirp Spread Spectrum (CSS)* that spreads the transmitted signal across a wide frequency band, resulting in improved robustness against interference and the ability to coexist with other wireless systems.

Wireless Technology	***IEEE 802.11ax (Wi-Fi 6/6E)***	***IEEE 802.15.4 (Zigbee)***	***LoRa (Long Range)***
Frequency Band	*2.4 GHz and 5 GHz/6 GHz*	*902-928 MHz in North America*	*902-928 MHz in North America*
Communication Range	*120 m in outdoor environments*	*10-100 m for line-of-sight communication*	*4.8 Km in urban areas and 16 Km in rural areas (line-of-sight communication)*
Multiple Access / Modulation Technique	*Orthogonal Frequency Division Multiple Access (OFDMA)*	*Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) or Time Division Multiple Access (TDMA)*	*Chirp Spread Spectrum (CSS)*
Data Rate	*600.4 to 9607.8 Mbit/sec*	*~ 250 Kbps*	*0.3-27 kbit/s*
Transmission Power	*High (50-100 mW)*	*Low (1-100 mW)*	*Lower (0.3-100 mW)*

Table 1 Characteristics of the wireless communications technologies that are the potential candidates to support the wireless controls in heliostat-based CSP systems.

The characteristics of the wireless communications technologies that are the potential candidates to support the wireless controls in heliostat-based CSP systems are summarized in *Table 1.* Very limited simulation and testing of the above technologies has been performed in the existing state of the art, and mainly in a controlled simulation environment *[7]*, *[8]*. Also, a comprehensive summary of the current deployment of wireless communications solutions by existing stakeholders, i.e., Company A-E (anonymized for intellectual property purposes), is presented in *Table 2.*

	Company A	***Company B***	***Company C***	***Company D***	***Company E***
Field size		*~100 to 250 m radius*	*100 m*	*0.06 km² (Approx)*	*1.5 km radius*
Heliostat size (mm^{22})	*27*	*2*	*7*	*37*	*26*
Wireless Topology (Access and backhaul)	*SmartMesh IP based mesh*	*Star*	*Multiple Star/autoconfigure mesh network*	*Star*	*Single star/Multi star*

Wireless Protocol (Access and backhaul)	*IEEE 802.15.4e with IPv6*	*Wi-Fi 6*	*IEEE-802.15.4*	*Wired with planned wireless this year*	*Proprietary protocol*
	IEEE 802.11 (Wi-Fi)				
Wireless Module	*LTC5800*	*Off the shelf Nordic Wi-Fi 6 module*	*TI CC1312R or TI CC1352R (heliostat side)*		*Not published*
Frequency Band (MHz)	*2400*	*2400 and 5000*	*868/915/2400*		*2400/915*
Data exchange Frequency & Latency (Periodic and Aperiodic)	*<80 bytes every 30s*	*Up and down ~200 bytes every ~10s*	*20-100 bytes every 100ms*	*95 bytes every 250ms*	*Not published*
	>90 bytes within 30s latency	*within 5-10s*	*Software update profile 1MBPS*	*24 bytes in the downlink every ~minute*	

Table 2 Wireless communications solutions by existing stakeholders

Table ***3*** contains the detailed wireless Wi-Fi/ZigBee modules specifications, while *Table 4* presents the associated wireless modules costs. Modules adhering to Wi-Fi protocol standards typically exhibit an anticipated communication range of approximately 120 meters in outdoor settings, unless specified otherwise. In contrast, modules utilizing ZigBee protocol standards typically offer a communication range of 10-100 meters for line-of-sight scenarios, unless specified differently.

Module	***Tx Power (Max)***		***Rx sensitivity***		***RSSI range***		***Band, Channel Bandwidth***	***MCU, Programmable, Antenna, FCC***				***Communication Range/Networking Protocol***
WiMOD iM222A	*4.5 dBm*	*2.82 mW*	*-97 dBm*	*2e-10 mW*			*2.41-2.48 GHz, 5 MHz*	✓	✓	✓	✓	*Up to 500 m (Outdoor), (line of sight) ZigBee*

EFR32MG24 Multi Protocol Wireless SoC	*19.5 dBm*	*89 mW*	*-105.4 dBm*	*2.88e-11 mW*	*-100 to +5 dBm*	*1e-10 to 3.16 mW*	*2.4-2.483 GHz, 2.2 MHz*	✓	✓	*X*	✓	*N/A* *ZigBee, Proprietary 2.4 GHz*
TI CC2674R10 Multi Protocol	*26 dBm*	*398 mW*	*-105 dBm*	*3.16e-11 mW*	*-105 to -10 dBm*	*3.16e-11 to 0.1 mW*	*2.3-2.5 GHz*	✓	✓	*X*	✓	*N/A* *ZigBee, 6LoWPAN*
wi2wi WC640 Wi-Fi 802.11 a/b/g/n + Bluetooth + ZigBee	*18 dBm*	*63.1 mW*	*-97 dBm*	*2e-10 mW*			*Dual Band 2.4/5 GHz*	✓	✓	✓	✓	*N/A* *ZigBee, Wi-Fi (2.4 and 5 GHz Bands)*
RFM22B ISM Transceiver M	*13 dBm*	*19.95 mW*	*-121 dBm*	*7.94e-13 mW*	*Up to -20 dBm*	*0.01 mW*	*848-888 MHz, 895-935 MHz 150 KHz*	*X*	*X*	✓	✓	*N/A* *N/A*
TI CC1312R	*14 dBm*	*25 mW*	*-110 dBm*	*1e-11 mW*	*-110 to -15 dBm*	*1e-11 to 0.032 mW*	*861-1054 MHz, 100 kHz*	✓	✓	*X*	✓	*N/A* *ZigBee, Wi-Fi*

	13 dBm	*20 mW*	*-110 dBm*	*1e-11 mW*	*-110 to -15 dBm*	*1e-11 to 0.032 mW*	*359-527 MHz, 78 KHz*					
TI CC1352R	*14 dBm*	*25 mW*	*-110 dBm*	*1e-11 mW*	*-110 to -15 dBm*	*1e-11 to 0.032 mW*	*861-1054 MHz, 100 KHz*	✓	✓	*X*	✓	*N/A ZigBee, Wi-Fi*
	13 dBm	*20 mW*	*-110 dBm*	*1e-11 mW*	*-110 to -15 dBm*	*1e-11 to 0.032 mW*	*359-527 MHz, 78 KHz*					
NRF24L01	*4 dBm*	*2.51 mW*	*-94 dBm*	*4e-10 mW*			*2.4 GHz, 1 or 2 MHz*	*X*	✓	✓	✓	*N/A 2.4 GHz ISM Band*
LTP5901-IPM/LTP5902	*8 dBM*	*35 mW*	*-93 dBm*		*–90 to –10 dBm*		*2.4000-2.4835 GHz (15 channels)*					*300 m*

HCUCC.R1 ***A complete Heliostat Network and Motion Controller in a module*** ***Additional Options:*** *GNSS, secured channels*	*19dBm*	*80mW*	*-114 dBm*	*4e-12 mW*	*-120 to 15 dBm*	*1e-12 to 0.032 mW*	*868/915 MHz BW20kHz* ***Long-Dist. Profile***	✓	✓	*X*	✓	*>2 km*
	18dBm	*80mW*	*-90 dBm*	*1e-10 mW*	*-120 to 15 dBm*	*1e-12 to 0.032 mW*	*2400 MHz* ***Short-Dist. Profile***					*>100m*
	19dBm	*80mW*	*-100*	*1e-11*	*-120 to 15 dBm*	*1e-12 to 0.032 mW*	*868/915 MHz BW600 kHz* ***500 kbps data-rate profile***					*>250 m*

Table 3 Specifications of Wireless Wi-Fi/ZigBee Modules operating in ISM Bands

Module	***Company***	***Country***	***Unit Price ($)***	***FCC Certified***	***MCU Price ($)***
WiMOD iM222A	*IMST GmbH*	*Germany*	*1K @ US$9.28*	✓	*Built-in*
EFR32MG24 Multi Protocol Wireless SoC	*Silicon Labs*	*Mainly US*	*EFR32MG24A010F1024IM40* *1K @ US$3.42*	✓	*Built-in*
TI CC2674R10 Multi Protocol	*Texas Instruments*	*Mainly US*	*CC2674R106T0RGZR* *1K @ US$3.31*	✓	*Built-in*
wi2wi WC640 Wi-Fi 802.11 a/b/g/n + Bluetooth + ZigBee	*Wi2Wi*	*US*	*Requested*	✓	*Built-in*

RFM22B ISM Transceiver M	*HOPERF*	*China*	*US$1.95*	✓	*Microchip PIC16F1519 1K @ US$2.17*
TI CC1312R	*Texas Instruments*	*Mainly US*	*CC1312R1F3RGZR 1K @ US$3.51*	✓	*Built-in*
TI CC1352R	*Texas Instruments*	*Mainly US*	*CC1352R1F3RGZR 1K @ US$3.80*	✓	*Built-in*
NRF24L01	*Nordic Semiconductor*	*Norway*	*3 Pcs @ US$11.99*	✓	*Development Kit*
HCUCC.R1 ***A complete Heliostat Network and Motion Controller in a module***	*CaribouLabs*	*Israel*	*1k @ US$20*	✓	*Heliostat motion controls, IMU, kinematics, sun position model estimator, multi-channel heliostat data communication, software updates, cyber-security, etc.*

Table 4 Cost of Wireless Wi-Fi/ZigBee Modules operating in ISM Bands[2]

Table 5 provides the technical specifications for the wireless LoRa modules, while *Table 6* presents the corresponding module costs. Wireless LoRa modules typically demonstrate a standard communication range of approximately 4.8 kilometers in urban environments and up to 16 kilometers in rural areas when maintaining a line-of-sight communication link, unless specific variations are specified.

Module	***Tx Power (Max)***		***Rx sensitivity***		***Band, Channel Bandwidth***	***MCU, Programmable, Antenna, FCC***				***Communication Range***
RN2483A-I/RM104	*14 dBm*	*25.12 mW*	*-146 dBm*	*2.5e-15 mW*	*433/868 MHz*	✓	✓	✓	✓	*5-15 Km*
LoRa 1276-C1	*20 dBm*	*100 mW*	*-148 dBm*	*1.6e-15 mW*	*915 MHz*	*X*	✓	✓	✓	*2-20 Km*

[2] *Readiness of the modules' antennas for the heliostats field is still unknown.*

iM880B-L	*19 dBm*	*79.4 mW*	*-138 dBm*	*1.6e-14 mW*	*868 MHz*	✓	✓	*X*	✓	*Up to 15 Km*

Table 5 Specifications of LoRa Wireless LoRa Modules operating in ISM Bands

Module	*Company*	*Country*	*Unit Price ($)*	*FCC Certified*	*MCU Price ($)*
RN2483A-I/RM104	*MICROCHIP*	*US*	*1pc @ US$19.48*	✓	*Built-in*
LoRa 1276-C1	*SEMTECH*	*Mainly US*	*100 @ US$7.60*	✓	*Development Kit*
iM880B-L	*IMST GmbH*	*Germany*	*1K @ US$16.03*	✓	*Built-in*

Table 6 Cost of LoRa Wireless LoRa Modules operating in ISM Bands

Readiness of the modules' antennas for the heliostats field is still unknown.

E. Open Challenges and Future Directions

The current design of the heliostat-based CSP systems is mainly based on a single solar tower collecting the solar energy from the heliostats field. The master control system resides at the single tower that communicates in a wired manner with the heliostat array control systems which also communicate in a wired manner with the access points that are spread within the field. The common radius of the existing heliostat-based CSP systems ranges between 1 Km to 2 Km and the current communication among the heliostats and the master control system ranges in the order of magnitude of few seconds. Different types of wireless communications protocols have been considered, ranging from very low frequency bands at the range of MHz, such as Zigbee (e.g., 868.0–868.6 MHz in Europe, 902–928 MHz in North America) and LoRa (863–870/873 MHz in Europe and 902–928 MHz in North America) to very high frequency bands at the range of GHz, such as Wi-Fi (e.g., 2.4 GHz) and high-band mm-wave 5G networks (e.g., 6 GHz-100 GHz). The current association of the heliostats to the access points is mainly static and pre-decided. The main wireless controls topology that is currently adopted is either single-star *[12]*, *[8]* or multi-star hierarchical topology *[14]* enabling the communication of the heliostats with the access points. The corresponding cost to implement the wireless controls ranges between a few hundreds of USD dollars per unit of heliostats considering large heliostats.

The design of the next generation wireless controls heliostat-based CSP systems envisions a short-range wireless communications topology in the order of magnitude of tens of meters, supporting a communication latency among the heliostats and the access points at the order of magnitude of 100s of milliseconds. A medium frequency band is considered as a good candidate to support the wireless controls in the next generation heliostat-based CSP systems, where the heliostats will dynamically form wireless communications topologies. Different types of topologies can be followed, such as high speed (Mbps-Gbps), low delay, single-star topology for smaller CSP systems or low speed (Kbps), long range mesh networking topologies for larger CSP systems or a combination of both by creating different wireless communications zones in the heliostats field, clustering models of the heliostats, and exploiting next generation communication technologies, such as the integrated access and backhaul (IAB), the non-orthogonal multiple access communication technique, and others. For example, Non-Orthogonal Multiple Access (NOMA) is a multiple access technique used in communication systems to allow multiple transmitters to share the same time and frequency resources, even if their signals are not orthogonal (i.e., they overlap in time or frequency). NOMA achieves this by encoding transmitter's information with different power levels or codebooks, enabling simultaneous transmission and reception of multiple signals on the same channel, with transmitters distinguished by their power or code domain. This technique optimizes spectral efficiency and increases capacity in wireless communication systems by accommodating multiple transmitters with varying signal strengths or quality-of-service requirements within the same communication resource, making it particularly useful in densely deployed communication systems *[16]*. A realistic goal of achieving a latency of *less than 100 ms should be targeted to enable closed loop autocalibration.* Also, part of the CSP systems community focuses on the design of multi-tower CSP systems, where few hundreds of heliostats target the corresponding tower, where they are affiliated to, in order for the energy to be exploited. The ultimate goal is to achieve a $50/sqm heliostat cost and levelized cost of electricity of $0.05/kWh. Focusing on the networking key performance indicators that are targeted in the next generation wireless controls heliostat-based CSP systems, as envisioned by CaribouLabs attempting to support the full autocalibration in the CSP system, they can be summarized as follows:

1. Latency: 50 msec
2. Data rate: 0.1 – 0.5 Mbits/s
3. Transmission power per transmission: 100-200 mW (with less than 20 mW in an extreme case scenario)

F. Towards Designing Next-Generation Wireless Heliostats

Apparently, the design of wireless heliostat-based CSP systems that leverage next generation networking technologies to guarantee undisrupted connectivity of the heliostats, regardless the field size, with the central station is still in its infancy. Also, the major problems of dynamically identifying access points and relays/repeaters within the heliostats' field remain notably unsolved. Additionally, the critical issues of identifying feasible routes in terms of heliostats energy availability and network traffic for the information transmission from and to the heliostats versus the star topology have not been addressed in the literature. Aiming to take a first step towards filling this gap, the HELIOCOMM team introduces the HELIOCOMM system, a modular system that supports the following functionalities.

i. The dynamic clustering of the heliostats based on their topology and networking characteristics, and the identification of the clusterhead in each cluster by additionally considering the heliostats' energy availability as determined by the harvested energy from their attached PV after considering the operational energy cost.

ii. The entropy-based routing of the transmitted information from each heliostat to the central station accounting for the heliostats' energy availability and the network traffic in order to guarantee minimum end-to-end latency constraints.
iii. The joint maximization of each heliostat's energy efficiency and minimization of its end-to-end latency via implementing an intelligent bandwidth splitting in the access and backhaul communication links at each clusterhead following the principles of the IAB technology. The corresponding optimization problem is formulated as a two-stage optimization approach at the access and the backhaul links to determine the optimal transmission power of each heliostat to achieve its Quality of Service (QoS) prerequisites, as defined by the Quantified Performance Targets (QPTs).

The architecture of the HELIOCOMM system, as well as the flow of control and information, are presented in *Figure 5* and its building components, which are currently developed at the University of New Mexico, are described in detail below.

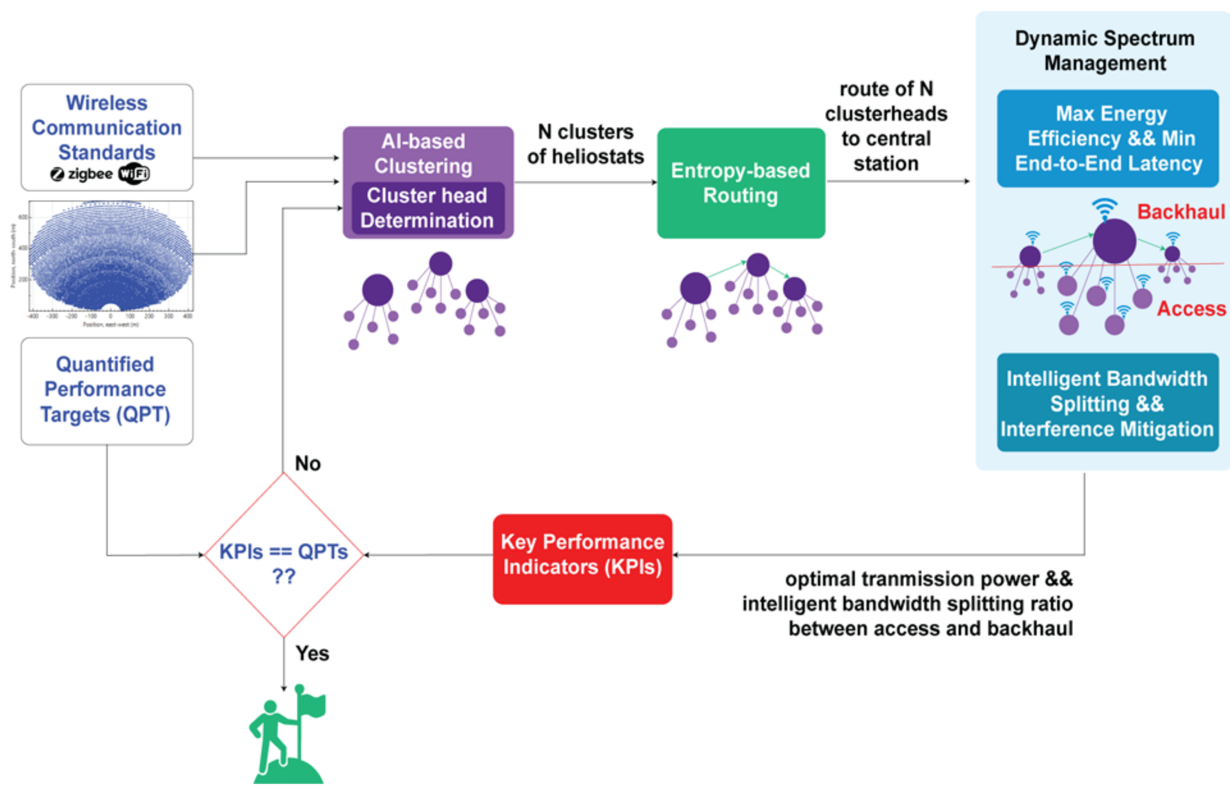

Figure 5 Architecture of the HELIOCOMM system and flow of control and information.

Initially, the HELIOCOMM system tests several wireless communications protocols in different ISM bands, such as 902-928 MHz, e.g., IEEE 802.15.4 (Zigbee, 6LoWPAN), 2400-2483 MHz, and/or 5150-5825 MHz, e.g., IEEE 802.11ax (Wi-Fi 6E), in terms of their appropriateness with respect to the transmission distance, power consumption, achievable data rates, and flexibility of modulation and multiple access techniques. Also, the QPTs are provided as input to identify the quantitative goals of the HELIOCOMM system, such as end-to-end latency, packet error probability, packet losses, energy consumption, transmission power, energy efficiency, and network reconfiguration and routing setup time.

After the initialization phase, the artificial intelligent (AI) based heliostats clustering and clusterhead selection is performed following a Q-learning-inspired approach. The distance and communication channel characteristics (as measured by the Received Signal Strength Indicator – RSSI) are exploited to define the probability of two heliostats belonging in the same cluster. Then, a Q-learning-inspired algorithm is designed to enable each heliostat that acts as a Reinforcement Learning (RL) agent to choose to be connected with another heliostat and form a cluster, i.e., actions. To balance the RL algorithm's exploration and exploitation processes and improve its computational complexity to converge to a stable clustering in the overall heliostats field, several variations of ε-greedy strategies are tested. Given the heliostats' clustering, the clusterhead selection for each cluster is performed following the closeness centrality approach and the heliostats' weighted sum of distance and communication channel gain from other heliostats belonging to the same cluster, as well as personal energy availability.

Given the heliostats clustering and clusterhead selection, an entropy-based routing is performed among the clusterheads to ultimately forward the information to the central station for further processing to support the autocalibration and closed-loop controls in the heliostats field. The entropy-based routing dynamically determines the optimal routes accounting for the clusterheads energy availability and network traffic. The clusterheads act as IAB nodes collecting the information from the heliostats belonging to their own cluster through the access link with an one-hop connection, and forwarding in a wireless multi-hop manner in the backhaul link to the central station, i.e., IAB donor.

The IAB nodes are critical nodes in the network in terms of their resource savings, as well as the rest of the heliostats given their strict energy constraints. A two-stage optimization problem is solved at each IAB node to determine its optimal transmission power and intelligent bandwidth splitting in the access and backhaul links towards jointly maximizing the energy efficiency and minimizing the end-to-end latency experienced by all heliostats in its cluster. The two-stage optimization problem is split between the access and the backhaul in order to ultimately optimize the experienced energy efficiency of each cluster-heliostat, i.e., cluster-node, as well. Towards minimizing the end-to-end latency experienced in each route, information about the transmission power levels and the bandwidth splitting in the access and backhaul links should be exchanged among the IAB nodes belonging to the same route. The multiple two-stage distributed optimization problems within each route are solved in parallel and information is exchanged among the IAB nodes based on beacon signals until the system converges to an optimal feasible transmission power of each heliostat while satisfying the end-to-end latency constraint as identified by the system operator.

Currently, the system will be implemented at the University of New Mexico, USA and operational prototype is expected to be available by 2026.

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